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Benefit Analysis Of Nondestructive Testing For Roadway Management

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**BENEFIT ANALYSIS OF NONDESTRUCTIVE TESTING FOR ROADWAY
MANAGEMENT**

A Major Qualifying Project Report
submitted to the faculty of the
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science in
Management Engineering
by

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Abstract

Nondestructive testing of asphalt with use of a falling weight deflectometer is a method by which transportation engineers determine the depth and rigidity of a given sample of a roadway without having to destroy the surface to take core samples. A comparison to destructive testing reveals that the cost-savings of nondestructive testing are high. This is primarily because of the reduction in labor.

Executive Summary

Nondestructive testing (NDT) of asphalt with use of a falling weight deflectometer (FWD) is a method that allows transportation engineers for municipalities and private engineering firms to gauge the characteristics of a roadway in situ. Specifically, depth and rigidity are able to be tested with the falling weight deflectometer.

The ability to measure depth is important because it allows transportation engineers to know where different layers of asphalt start and end, and allow them to know where the subgrade, or existing Earth material, is located.

An accurate measurement of rigidity enables transportation engineers to understand how much displacement an asphalt system has relative to the load applied. The ability to measure depth and rigidity allow transportation engineers to gain an understanding of the quality of the material that exists in the roadway. From this they are able to make informed decisions when prioritizing rehabilitation projects.

A combination of direct interviews and research of refereed publications on the topic were used to analyze the benefits of nondestructive testing. A cost analysis study of nondestructive testing versus destructive testing was performed to analyze the savings of one method over the other.

The results indicate that there is a marked savings when using the falling weight deflectometer as a nondestructive testing method. Two significant factors that led to these savings were:

1. time spent in the field is decreased, on average, by forty-three minutes per mile
2. labor needed to perform the testing in the field decreases from four laborers to only one laborer

Nondestructive testing was found to save approximately 80% the cost of destructive testing, not including the initial investment.

The recommendation of this study is that larger road projects can capitalize on cost savings by using nondestructive testing.

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Introduction and Literature Review

America's Highways

America's highways are critical for the proper functioning of the United States economy. The Federal Highway Administration (FHWA) acknowledges that through infrastructure investment, there is potential for a gain in the output of industry. Macro- and micro-econometric research by the FHWA tries to answer the question, "How do changes in highway investment translate to private productivity at the national level?"¹

The National Highway System (NHS), consisting of Federal Highways and US Interstates, represents only 4% of the 160 million miles of roadways that connect population centers, airports, border crossings, tourist destinations and access between cities and regions. However, the NHS accounts for 40% of the nation's traffic. Moreover, 70% of truck freight traffic is generated by the NHS.¹

A reliable and efficient transportation system is demonstrated to have positive effects on the private sector as it:¹

1. generates innovative distribution systems
2. decreases inventory costs by utilizing just-in-time (JIT) delivery techniques
3. lower cost of service or product due to decrease in cost of logistics
4. access to larger input and labor markets, leading to an increase in resources and talent

¹ Keane, Thomas F. "The Economic Importance of the National Highway System" Federal Highway Administration, Spring 1996 <<http://www.tfhrcc.gov/pubrds/spring96/p96sp16.htm>>

Economic Analysis on the Impact of Roadway Investments

There is a relationship between the national productivity level and investments made by government to the national highway system. This relationship is studied by the Federal Highway Administration's economists. They use a variety of macro- and microeconomic tools to help them determine how investments made in a specific part of the national highway system can impact productivity.¹

Macroeconomic Analysis

The FHWA uses macroeconomic analysis to determine the relationship between transportation and economic growth. The primary methodology for determining this relationship is using the production function. Research done estimates that a ten percent increase in investment in the NHS yields about a 4% increase in the national productivity level.¹

However, since transportation projects that are picked compose of just a small portion of the entire NHS, recent research has concentrated mostly on microeconomic analysis at the industry- or firm-level.

Microeconomic Analysis

Research from the FHWA on manufacturing companies shows a positive impact on firm productivity when there is infrastructure improvement. The positive change is attributed to a reliable and efficient transportation network which is a part of the production process.

Service industries, such as communications and utilities, are also able to increase productivity given a transportation network that operates more efficiently in allowing its employees access to its equipment and customers.¹

Importance of the System

Based upon the research and statements of the FHWA, it is evident that the NHS is critical to maintaining and growing the economy. An effective transportation system positively impacts the economy. An inefficient transportation system, one that is in disrepair or one that is over capacity causes delay for the industries that rely on the highways to deliver goods to customers and transport its employees to work. Delays translate to potential productivity decreases for industry through missed deadlines for delivery or longer production processes.²

Flexible Pavements

It is important to understand the basic concepts of a standard roadway in order to understand the nature of the research presented in this paper. The characteristics of the material and the different types of material used are discussed.

Flexible pavements are a multilayered elastic system. It is multilayered because there are different types of asphalt laid out in different layers. The term elastic is a description of the characteristics of the system. As a load is applied to the asphalt it is displaced along the perpendicular axis. The roadway, which

² Garber, N. J., and Hoel, Lester A. Traffic and Highway Engineering 3rd Edition. 2002.

consists of all the layers, is one piece of a transportation facility. A transportation facility is the entire highway including roadway, shoulders, signage, lights, shrubbery/foliage, etc.² A brief overview of each layer is provided.

Flexible Pavement Layers

Subgrade

The subgrade layer of an asphalt system is the existing material of the Earth. Essentially it is the rock and dirt that was already in place. The American Association of State Highway and Transportation Officials (AASHTO) is one body that sets standards for soil classification.

Classification is based upon systematic categorization according to probable engineering characteristics. Some characteristics that are taken into consideration are surface texture, porosity, void ratio, moisture content, degree of saturation, density of soil, permeability, and shear strength.² This layer is also referred to as the prepared road bed.²

Figure 1 shows an example of subgrade. It is simply the bottommost layer of the roadway and the existing material, represented here as compacted dirt.



Figure 1: Subgrade
Source: Nevada Department of Transportation

Subbase

Subbase, located immediately above the subgrade or prepared road bed, is of superior quality to the subgrade in terms of plasticity, gradation, and strength. If the roadway specifications specify a subbase that has the same qualities of the subgrade, then the subbase layer may be omitted.²

In Figure 2, the subbase is shown. In this example it is crushed stone that has been spread across the project site and compacted. It is ready to receive the base course of asphalt.



Figure 2: Subbase
Source: Nevada Department of Transportation

Base Course

The base course consists of granular material mixed with asphaltic concrete. Asphaltic concrete is the binder which holds together the aggregate material. It is the black liquid that gives roads their signature black finish.² This layer is monitored for appropriate plasticity, gradation, and strength. Plasticity is a measure of the moisture content of a material before it crumbles. Gradation refers to the size of the aggregate in the mix. For the base course, larger pieces of aggregate (larger in surface area and in physical size) are used compared to the surface course.²



Figure 3: Base Course
Source: Virginia Department of Transportation

The construction presented in Figure 3 shows the base course being laid on top of the subbase. It is approximately 4" thick. On top of this layer will be the top most layer, the surface course.

Surface Course

The course that most motorists are familiar with is the top layer. Similar to the base course it is an asphaltic concrete mixture, consisting of asphalt and mineral aggregate. The properly formed surface course is able to withstand high tire pressure, resist the abrasive force of traffic, provided a skid resistant surface, and prevents penetration of surface water to the layers below.²

The surface course will be the layer that lane markers will be painted onto. Figure 4 is one example of a completed roadway, the visible layer of which is surface course.



Figure 4: Surface Course
Source: New York State Department of Transportation

The ability to withstand high tire pressure is important for maintaining optimal road conditions. If the material in the road were easily affected by a load application then every time a car drove over it there would be a chance that aggregate could strip from the binder or the surface could crack, allowing water to enter the roadbed.²

If the surface layer is unable to provide a seal against water than it may become possible for water to seep into the roadway and fill voids between aggregate and binder. This becomes an issue in colder climates when such a situation is exposed to the freeze/thaw cycle. As the water expands it can further act as an agent for stripping binder from aggregate.

Forces Acting On Flexible Pavement

When a load is applied to an asphalt system, several assumptions are made. These assumptions are standards set by AASHTO, the American Society

for Testing Materials (ASTM), and the American Society of Civil Engineers (ASCE). These assumptions are used to set similar conditions in testing that happens nation wide.⁵

1. The load applied is vertical and compresses the top layer of asphalt
2. The different layers of asphalt have a finite vertical measurement, but extend horizontally forever (referred to as an infinite elastic half-space).

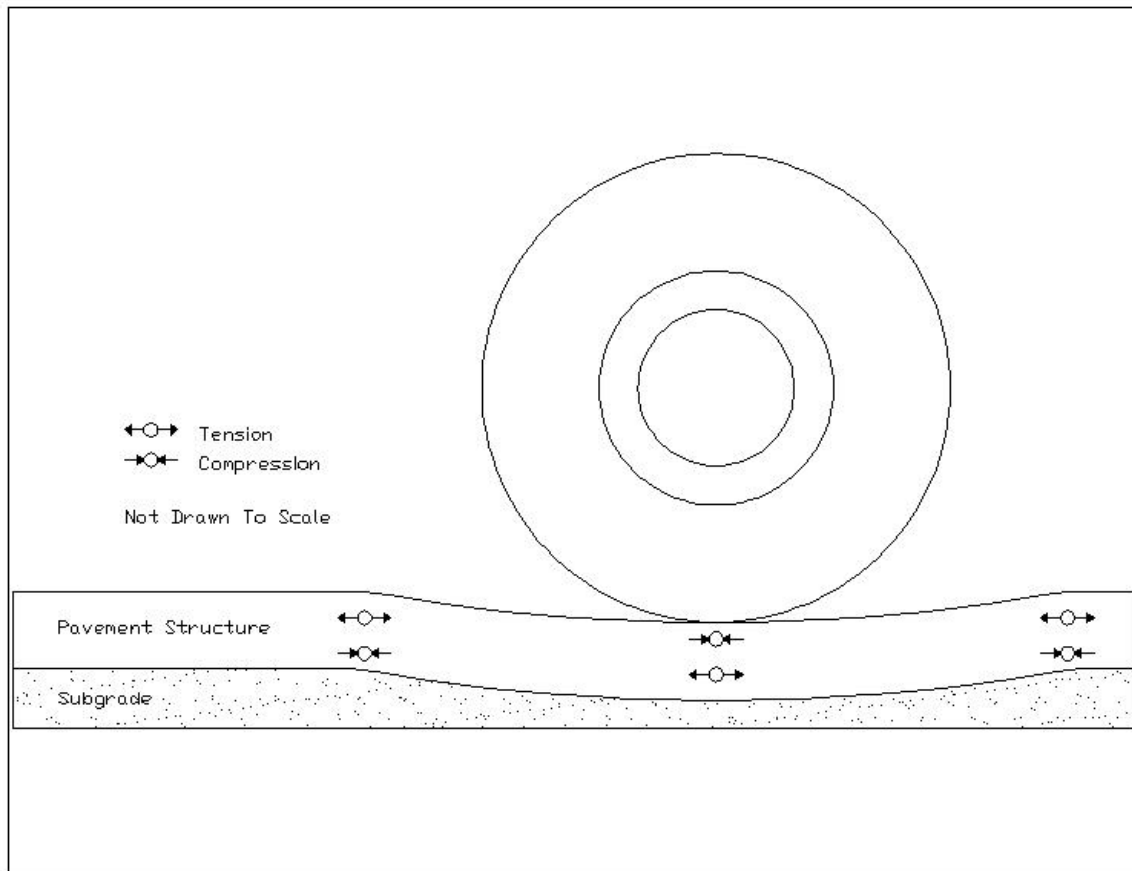


Figure 5: Schematic of Tensile and Compressive Stresses in Pavement Structure³

Figure 5 represents how a standard asphalt system is subjected to both compression and tension from a dynamic or static load applied from normal

³ Thickness Design – Asphalt Pavements for Highways and Streets, Manual Series Number 1, Asphalt Institute, Lexington, KY, February 1991.

traffic movement. The forces acting on a pavement system are what lead to deterioration or failure.

The speed at which deterioration and failure can occur can be influenced by the weather. For example, a particularly hot environment can set the normal temperature of the system to a degree that increases the elasticity of the system, bringing the system closer to permanent deformation (described below).

Extreme cold, conversely, can subject asphalt to the freeze/thaw cycle which can promote loss of cohesion between aggregate and binder (described below).

Failure of the Pavement System

Permanent Deformation (Rutting)

As asphaltic concrete is an elastoviscous material, it can, in certain regards, be treated as a spring. That is, if a certain point is passed in terms of force applied, the asphalt will not return to its original (or rest) state.

The term elastic applies because as a load is applied to asphalt, the flexible nature of the pavement is to slightly shift. When the load is no longer applied the asphalt returns to its previous form. The term viscous refers to the asphalt's characteristic to resist change.

For asphalt, there is a difference between elastic and plastic when defining systems characteristics. Elasticity refers to the ability of the asphalt system to change when a load is applied and plasticity refers to the percentage level of moisture at which the asphalt system is compromised.²

Deformation manifests itself on the surface of an asphalt system as longitudinal depressions along vehicle wheel paths. It is most commonly seen at

intersections and bus stops where heavy loads are applied for longer than average periods of time.

Excessive rutting can accelerate other forms of structural deterioration, as it weakens the overall system. A permanently deformed section of asphalt has increased potential for cracks which can lead to moisture being absorbed by the system. Through the process of the freeze/thaw cycle, this could expose a roadway to an increased chance of stripping, as described below.⁴

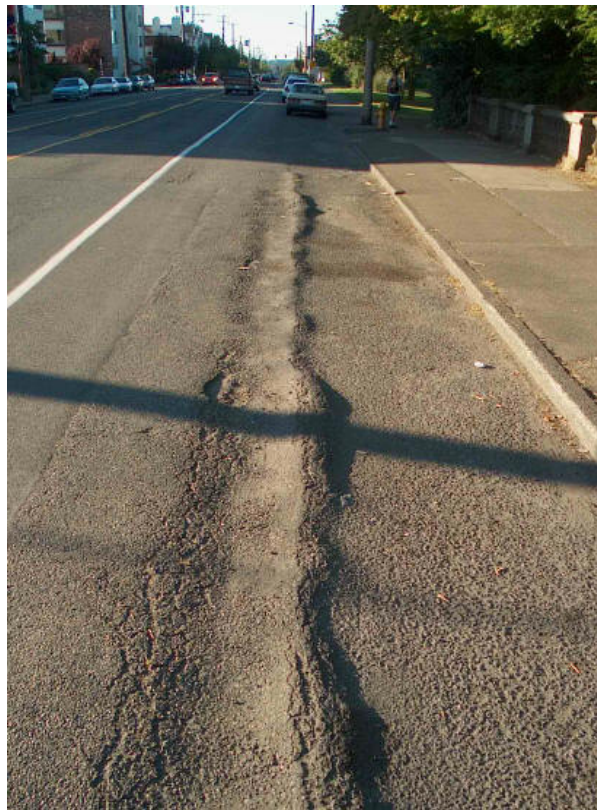


Figure 6: Rutting
Source: Washington State Department of Transportation

⁴ Myers, L.A. and D'Angelo, J. "Evaluating the field performance of asphalt mixtures in the lab," Public Roads.

Excessive rutting can cause vastly uneven surfaces that present a risk to motorists. Rutting represents an accumulation of small deformations over an extended period of time.⁵

Figure 2 represents an extreme case of rutting. Rutting can be a source of potential hazards and accidents to pedestrians, bicyclist, and pedestrians.

For pedestrians, the rutting presents an uneven surface that can present itself as a potential tripping hazard. Rutting can also cause improper drainage of the surface by blocking the flow of water from the surface towards the shoulder and drainage systems. The pooling of water presents a chance for hydroplaning by motorists. In colder climates, pooled water can cause icy conditions on the roadway, a potential hazard to motorists and pedestrians alike.

Rutting may also create hazards by directing a vehicle's wheel path contrary to the intended direction of the operator. In a case as seen in Figure 2 above, the wheel path can be "guided" by the ridge of asphalt formed by permanent deformation.

Loss of Cohesion (Stripping)

Stripping occurs when the asphalt binder is stripped from the aggregate in an asphaltic concrete mix. As stripping occurs, voids are created in the asphalt. These voids can fill with water, and through the process of the freeze/thaw cycle may potentially expose the roadway to increased chance for cracking and potholing.

⁵ Haas, Ralph and Hudson, W. Ronald. Pavement Management Systems. 1978.

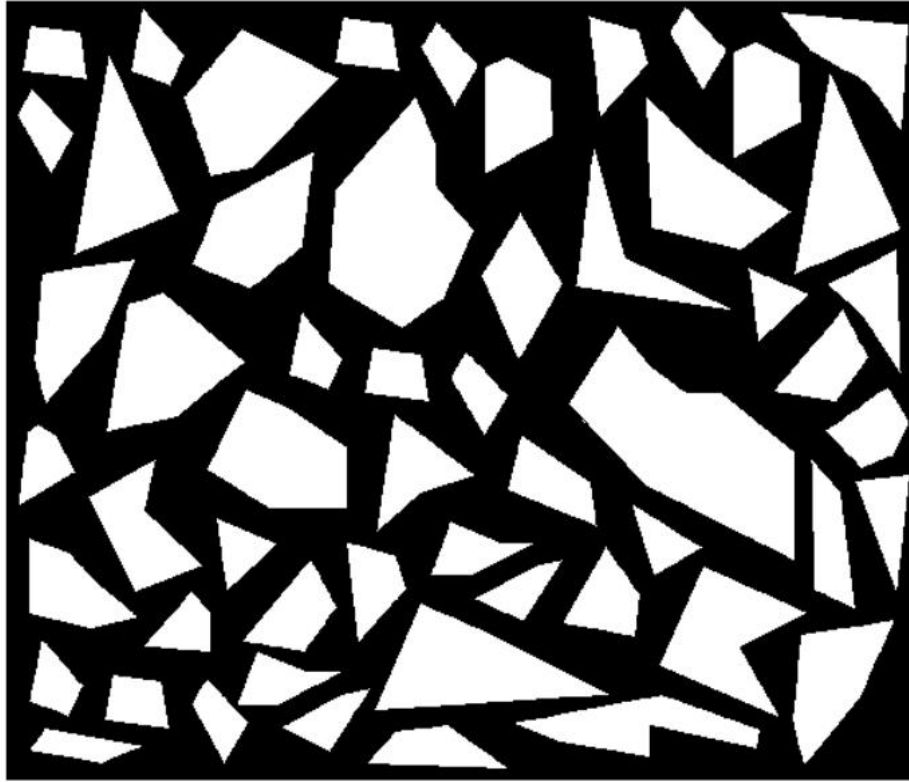


Figure 8: Asphalt Cross Section (Undamaged)

Figure 8 represents an undamaged portion of asphalt. The white space represents the aggregate and the black space represents the asphalt binder holding the aggregate together. The figure is not drawn to scale.

Figure 9 represents a close up on a portion of a cross section. Again, the white space represents aggregate and the black space represents the asphalt binder. The gray space between the largest aggregate piece and the binder represents a void space, potentially filled with air or water. If water breaks through the seal at the surface it can potentially flood the void between the binder and aggregate. In colder climates, the freeze/thaw cycle can cause the void to expand along with the water, creating more void space when the water thaws. As the process continues it can become increasingly worse for the roadway.

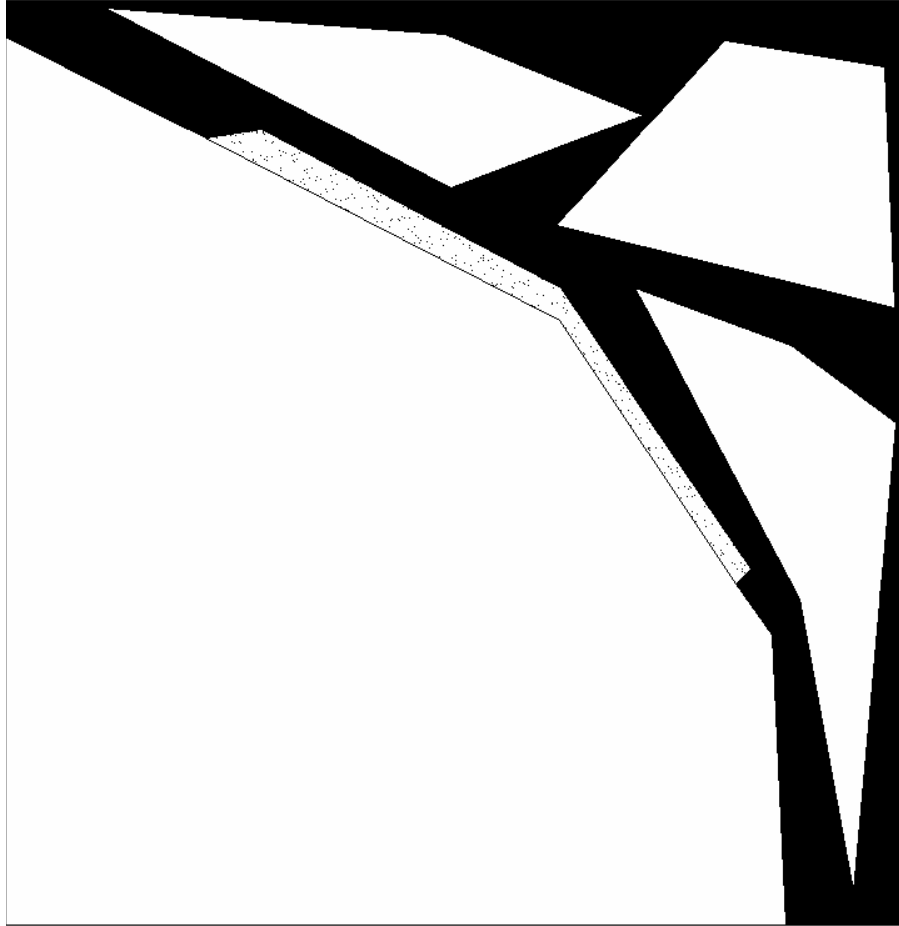


Figure 9: Asphalt Cross Section With Voids

Triaxial Testing

Purpose of Triaxial Testing

The number one cause of distress in an asphalt system is stress from an applied traffic load.^{4, 6} Sheer deformation, as mentioned earlier, is caused by the applied traffic load. As early as the 1940's, triaxial testing was being used to determine "the behavior of a mix in respect to bearing power of the aggregate and of the mix."

Triaxial testing is a destructive test by which a core sample of asphalt is taken from a roadway and then taken to a lab for testing. The core sample has a

load applied across one of its axis. The axis that is perpendicular to the applied load experiences some amount of expansion as a result of the load being applied. These tiny shifts are measured and expressed as a ratio of the expansion versus the radius of the core sample.⁶

Methodology for Triaxial Testing

A core sample of asphalt is loaded into an apparatus which performs a mechanical test. The core is removed by using a special drill. Its drill bit is a hollow circle of 6" diameter for highway samples and 8" for airport runways. The drill bit has the capability of drilling up to two and one-half feet to reach the bottom of the roadway to the preexisting subgrade. The most common samples are taken from the wheel path of a roadway as this is the portion of the roadway that is subjected to the most loading. The test applies a load axially to the cylindrical specimen. The core samples used for a triaxial test followed a ratio of 2:1 relating the height to the diameter of the sample. For example, a core sample of diameter equaling 4" would have a height of 8".⁷

Figure 10 shows a highway engineer removing a core sample from a roadway. Figure 11 shows a sample already removed from the roadway.

6 Endersby, V.A. "The History and Theory of Triaxial Testing and the Preparation of Realistic Test Specimens" Triaxial Testing of Soils and Bituminous Materials. Special Technical Publication Number 106, American Society for Testing Materials.

7 Smith, V.R. "Application of the Triaxial Test to Bituminous Mixtures" Triaxial Testing of Soils and Bituminous Materials. Special Technical Publication Number 106, American Society for Testing Materials.

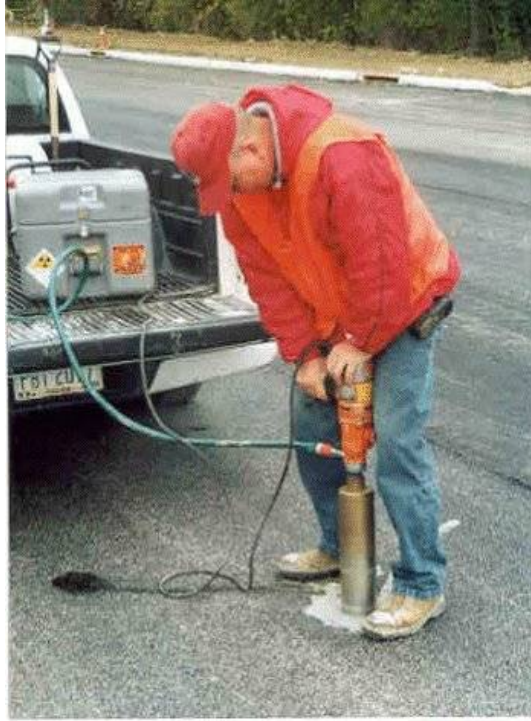


Figure 10: Core Sample Being Taken
Source: Oregon Department of Transportation



Figure 11: Core Sample
Source: WPI Asphalt Lab

First Major Application of Triaxial Testing

One of the earliest state government agencies to use Triaxial testing for pavement management was the State Highway Commission of Kansas. As early as 1941 they had run several hundred tests on both base and paving materials. Their results were interpreted with respect to the modulus of deformation. The modulus of deformation is the ratio between the load applied and the expansion of the sample along the perpendicular axis. This is an important measure of the sample because it allows engineers to know the elasticity of the sample.⁶

$$E^* = \frac{1}{\sqrt{J_1^2 + J_2^2}}$$

Equation 1: Modulus of Deformation⁸

$$J_1 = \frac{\text{component of strain in phase with stress}}{\text{Stress}}$$

Equation 2: Component of Strain in Phase with Stress⁸

$$J_2 = \frac{\text{component of strain at } 90^\circ \text{ to stress}}{\text{Stress}}$$

Equation 3: Component of Strain 90 Degrees Out of Phase with Stress⁸

Shortcomings of Triaxial Testing

Triaxial testing had some shortcomings. Specifically, there was no ability to test an asphalt sample through dynamic loading. The process was also time consuming.

⁸ Croney, David; Croney, Paul. The Design and Performance of Road Pavements. McGraw Hill Book Company, 1991.

No Dynamic Loading

As stated, the goal of triaxial testing was to be able to have a singular test that accurately and consistently measured the modulus of deformation. Dynamic loading was not able to be applied in triaxial testing. Dynamic loading would more accurately mimic the wave deflections that are normally associated with traffic loading applied to an asphalt system. As early as 1950, researches realized that to understand how dynamic loads affect asphalt it would have to be investigated through an alternative method.⁶

Resource Consuming

Another shortfall of triaxial loading was the time and expense that had to be invested in order to run the tests associated with triaxial testing. Each coring sample would typically take 30 minutes to remove from the roadway and fill in the hole that it left. The manpower associated with these activities is four laborers. The need for laborer was two for drilling and two for filling. There were two types of triaxial tests with respect to this issue: samples prepared in a lab and samples taken from the field.⁶

For lab samples, multiple tests had to be run several times to ensure that the results were significant. The standard at the time was to run a test three times to ensure accuracy. Also, multiple samples had to be tested to ensure significance of the material. The bare minimum would be six samples tested three times a piece. While this may seem like a small amount of tests to run, the time it takes to run the test, is the shortfall of the system. The measurements of the triaxial test are viewed, recorded, and checked by a lab technician.

Moreover, the samples being tested were only good for theorizing potential permanent deformation. That is, what load needed to be applied before the asphalt became permanently deformed? The reason for this was that lab samples were not compacted in a method similar to the asphalt in the field. Triaxial testing was used to test samples from the field and potential new mixes were created in the lab but were not formed with the same standards as those in the field. Asphalt compacted in the field with vibratory roller forces the larger aggregate to arrange with their longest plane parallel to the surface. Lab samples were just as likely to have their larger aggregate pieces perpendicular to the same plane.⁶

For samples obtained from the field, sample extraction was a time consuming process. Often times using a power tool to drill up to 10" deep of asphalt took time. As stated earlier, up to fifteen minutes of time was required to remove the sample. Multiply that out over the numerous samples that needed to be removed and time quickly becomes a cost liability. At the time, there was no expectation to shorten the process in terms of removing the asphalt from the roadway. The direction of research at the time focused on moving towards a faster test in the lab. The best practices at the time suggested removing samples every 500 feet.^{6, 7} This usually required engineers to stop at a site and then move to the next one. The constant starting and stopping of the laborers along the roadway did prevent a safety concern. A secondary issue was that due to the time devoted to removing a piece of roadway required making the roadway unavailable for motorist use.

Researchers realized that “this procedure requires a great deal of time and expense to test one specific material.”⁷ Research at the time recommended finding a method for “speeding up time spent analyzing samples in the lab.” At the time, the equipment they would have needed would need to record response to the load applied digitally.

Nondestructive Testing (NDT)

Nondestructive testing tests for the elastic modulus of an asphalt system in situ. Elastic moduli are used to characterize the stress strain behavior of a pavement system; elastic moduli in turn are used to determine deterioration and cracking. There are numerous methods that have been developed to determine the elastic moduli; however four are regarded as the most popular methods: (1) static deflections, (2) steady-state dynamic deflections, (3) impact load response, (4) and wave propagation. Elastic moduli as discussed in non-destructive testing are analogous to the modulus of deformation discussed during triaxial testing (the relationship between the deformations of asphalt related to the load applied).²

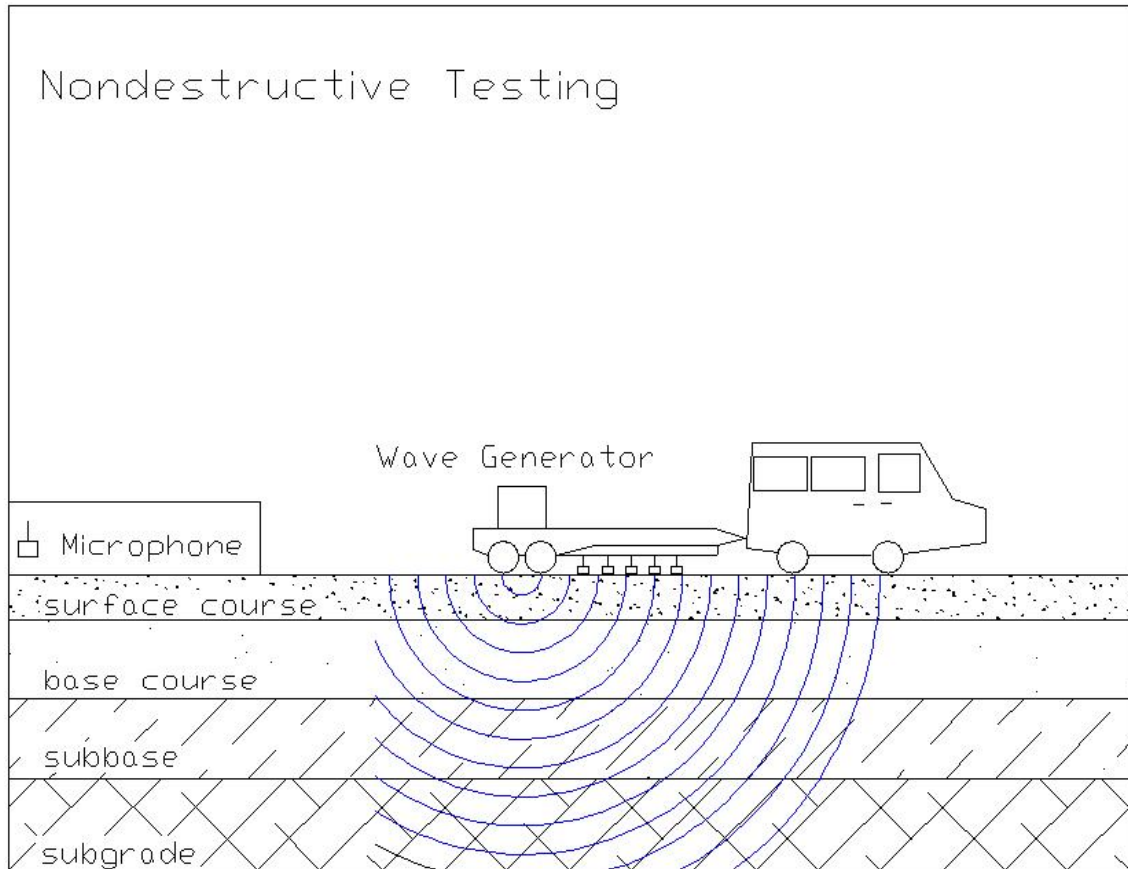


Figure 12: Nondestructive Testing with Wave Propagation ⁸

Wave Propagation

The wave propagation method of nondestructive testing will be the focus of this paper. Wave propagation methods measure the velocities of the primary waves traveling through the pavement system. This process differs from other nondestructive methods. Other systems commonly use vibration sources or load bearing methods. The waves travel through the individual layers of the entire pavement system. Therefore, by measuring the progression of the wave through the different layers, the test is able to measure the depth of the roadway and where there are changes in layer (for example, between surface course, base course, and deeper). Such research has been compiled in the *Transportation*

Research Record. The article “Moduli of Pavement Systems from Spectral Analysis of Surface Waves” documents such research in detail.

Steady State Wave Propagation

The steady-state technique uses a vertically oscillating object placed on the surface of the system being tested. The oscillating mass excites the system being tested by producing Rayleigh waves. Next, motion transducers are then placed on the surface and moved until a pattern is reached between the successive peaks or corresponding reading received. If low frequencies are received long wavelengths will appear, this is directly related to the depth of the site being tested. Corresponding high frequencies with shorter peaks would mean shallower testing. However, one drawback of the steady state is the length of time required to gather the necessary data to determine specific moduli of a certain site. Data acquisition at only one single site may take up to several hours. This is dependent upon the equipment used and the degree of accuracy required. This process could be achieved by a wave pulse caused by an impact of the pavement surface and spectral analysis performed.⁹

Pavement Life

Pavement life is generally defined as the length of service that a particular pavement system can be used before maintenance or rehabilitation is required.

⁹ Yuan, Deren; Nazarian, Soheil; Chen, Dar-Hao; Hugo, Fred. “Use of seismic pavement analyzer to monitor degradation of flexible pavements under Texas mobile load simulator” *Transportation Research Record*. n 1615, Aug, 1998, p 3-10.

This pavement life is usually determined by performing non-destructive seismic testing.

All pavement systems deteriorate over time. Typically, pavement deteriorates at an ever-increasing rate, at first very few distresses are present and the pavements stays in relatively good condition, but as it ages more distresses develop with each distress making it easier for subsequent distresses to develop. For instance, once a substantial crack occurs it is then easier for water to infiltrate, penetrate, and weaken the subgrade. Maintenance and rehabilitation are the two principal treatments used to extend pavement life. These treatments will immediately improve the pavement condition and affect the future rate of deterioration. In general, maintenance can slow the rate of deterioration by correcting small pavement defects before they can worsen and contribute to further defects. As already stated above, small damage can lead to bigger damage by subjecting the roadway to potential for new types of damage. For example, a small crack in the road surface can subject the roadway to water penetrating the surface and through the freeze/thaw cycle, speed up the rate at which potholing or stripping can occur.

Beyond a certain point, however, defects become too large for correction by mere maintenance. At this point, rehabilitation can be used to effect a wholesale correction of a large number of relatively severe defects, which provides a step increase in pavement condition.

Importance of Issue

A major problem that highway engineers face today is not how to construct new pavements, but how to evaluate current roadways to meet the growing demands of overpopulated roads and higher magnitude of traffic loading and frequency.

Progress of Nondestructive Testing

Nondestructive testing of pavements has made substantial progress during the last two decades. The process itself has become much more efficient and the data received from these types of tests have become more viable.

Problem Statement

With the advances made in nondestructive testing over the past two decades and the need to exercise greater cost control in maintaining a growing and aging highway system, it is important to analyze the benefits of nondestructive testing over destructive testing. It is essential that the project team

It is the intention of this paper to analyze the advantages of nondestructive testing over destructive testing on the basis of cost, allocation of resources, safety, and time.

Methodology

The methodology section will define the process used to address the problem statement. Since there are always alternatives to solving a problem,

options were identified and evaluated to see which best met the goals of the project.

Background research was performed to create a basic understanding of the topic and a basis to perform the necessary work to generate conclusions and results. This section will provide detail upon the process taken to find those results. Previous research had been performed to gain the knowledge necessary to take the data collected throughout the project team's interviews and data queries and evaluate that data collect.

To generate conclusions and recommendations, historical data needed to be gathered on both destructive and nondestructive testing of asphalt. In addition to data on the testing of asphalt any relevant data on asphalt systems or asphalt properties in general was necessary to fully understand the concepts behind the asphalt testing process. This historical information was gathered through a process of archival research and by conducting interviews.

Archival Research and Literature Review

The term archival research pertains to information that has already been recorded. Archival data can sometimes be more difficult to obtain however; it is often times more accurate than other sources of information. Archival research consists of statistics, data bases, and records sometimes public and sometimes private.⁹

Throughout the course of the project, the project team was continuously researching accordingly to the current problem the team faced, whether it was information on asphalt systems themselves or on different types of asphalt

testing. First, the team began with the research of destructive and nondestructive testing data and processes. This information was gathered through archival research and through reviewing articles previously published on both destructive and nondestructive testing. As the study grew more advanced the team found themselves researching different topics such as pavement analysis, triaxial testing, and pavement life documents for example. Major sources for this research were that of previously published journal articles and other research proven and accredited by the American Society of Civil Engineers. These articles were found through extensive database searches and other archival research tactics.

Literature reviews and archival research played a vital role in the project. This method of acquiring previously recorded data enabled the project team's project to advance rapidly. Furthermore, research and data taken into consideration was provided by civil engineers and contracting firms who had previously performed work on the destructive testing and nondestructive testing of asphalt. Personal testing would generate the same results, and prove not to be economically feasible.

Archival and Literature Review for Destructive Testing

Archival research for destructive testing processes and data was conducted by the project team through libraries using numerous sources. Many publications regarding destructive testing were found in the Transportation Research Record. This journal is one of America's most prestigious and respected journals in the field of pavement systems and all related research.

One of the first articles for non destructive asphalt testing was published in 1982 by the Transportation Research Record. Prior to this date most testing had been destructive, therefore information gathered on destructive testing occurred using publications in the early 1980's or prior.

Archival and Literature Review for Non-Destructive Testing

Archival research and literature reviews for non destructive testing were also performed in addition to those of destructive testing. The Transportation Research Record was a major source for finding supporting data for nondestructive testing of pavement systems. Contrary to destructive data research, most relevant information was published post 1980, when research had begun to become intense on nondestructive testing corresponding to that of the fields leading researchers and more common usage of the process.

Interviews

One key element in conducting useful research is gathering reliable information. The project teams major focus when conducting interviews was gathering quality information that can be trusted, throughout the project team's work performed and the project team's archival research. One basis for doing that is designing questions and questionnaires that get the kind of information from which the researcher can draw valid conclusions. This method is one of the oldest methodologies for gathering data. By conducting a series of interviews throughout the civil engineering department, information was gathered on both destructive and nondestructive testing. Professors in WPI's asphalt testing lab were questioned. Rajib Mallick, professor of civil and environmental engineering

has years of work in the field of asphalt testing and possess the knowledge and expertise necessary to offer professional answers to questions asked. Questions asked consisted of cost related questions, equipment related questions and viability related issues. For example “How long does one individual test take?”. Complete questionnaires can be viewed in appendix A.

Graduate student Jonathan S. Gould gave the project team a demonstration of the nondestructive testing van on Friday, April 15. The demonstration included a ride around WPI’s Gordon Library parking lot.

Interview Structure

Interviews were created to generate information from chosen knowledgeable people previously discussed. The major topic of interviews conducted entailed three main categories, Cost of equipment, cost of processes, and viability of results from a particular system being tested. Corresponding questions were asked pertaining to the type of testing being researched.

Conducting Interviews

Aside from the project team actually performing the tests another viable way to gain information about the process of asphalt testing was to interview the appropriate people. We met with each qualified individual in the civil engineering department who had knowledge about pavement testing or characteristics of paving. This included both professors and lab technicians working in the WPI asphalt testing lab. These interviews enabled the project team to understand the thought behind nondestructive testing and help become more knowledgeable with the process itself. Specific questions were asked on research they had

performed and on potential sources to further the project team's research. More specific examples of questions can be seen on the questionnaire sheets attached in the appendix.

Data Organization

The data obtained throughout the project team's qualitative archival research and work performed needed to be organized in a manner that would make it easy to interpret. Necessary data consisted of cost information for all processes involved with both forms of testing. For analyzing and interpreting of the data that had been gathered the project team needed to decide on certain characteristics that would be crucial in the project team's decision for conclusions and future recommendations. This is where the economics and viability part of the project team's project was developed. Economic evaluation and data viability were chosen because they stand out among characteristics that must be taken into consideration for a contractor before choosing a process. If a process was inexpensive, but not viable the process would not yield acceptable results and may cause wrong decisions to be made. In turn bad data would lead to bad analyzing and cause work to be done over again or premature costing more money than that of a more expensive but more viable test. With the creation of a matrix this allowed the project team to evaluate certain characteristics of the different types of testing and to make the project team's conclusions from weighting each characteristic, viability and cost effectiveness, differently.

Below is the matrix that was created contains all categories that were taken into consideration when justifying the project team's recommendations.

	Cost	Human Resources	Safety	Time
Nondestructive Testing				
Destructive Testing				

Figure 13: Comparison Matrix

Work Performed

For each testing process time per test, field cost per test, lab cost per test, verification cost per test, and total cost per test was calculated per mile. In this section the project team will explain how the project team developed the costs listed above.

Destructive Testing Cost Formulation

To determine the test cost for destructive testing all aspects of the testing needed to be taken into consideration. The initial investment, field work costs, and lab work costs.

Initial investment costs consist purely of the cost of equipment needed to be purchased in order to first begin with destructive testing. Destructive testing costs consist of two trucks and one coring rig. These costs estimated by 2004 industry standards amount to approximately \$70,000.

Field work for destructive testing was formulated by calculating the number of workers needed for destructive testing, their pay rates, and amount of time it would take a destructive testing crew to test 1 mile of asphalt. It was determined that four workers would be necessary to perform destructive testing. Their pay rates were all noted as similar in 2004 at about 25 dollars. Time necessary to destructively test a one mile stretch of asphalt was calculated at 46 minutes. This takes into account the coring crew stopping two 15 minute coring

tests, and including a travel speed of 60mph. It is assumed that the patching crew patches the first hole while the coring crew bores the second sample. This time of 46 minutes coupled with the number of workers being paid at a rate of \$25 gives the project team the cost of \$76 per hour for strictly destructive testing field work.

$$.76 \text{ hours} * \$100 = \$76 \text{ per mile field work}$$

Equation 4: Destructive Test Field Work Cost

In addition to the cost of field work lab tests are necessary to determine the elasticity and rigidity of the asphalt. For destructive testing one lab technician is necessary. This lab technician working at a normal pace would take approximately 15 minutes to perform one lab test on one sample. One lab test is all that is necessary on one sample. Factoring in the industry standard wage for a trained lab technician of \$25 and the time per test, it is calculated that one lab test for destructive testing costs \$6.25. Two destructive tests per mile are necessary when determining the elasticity and the rigidity of an asphalt system so in turn two lab tests would be necessary giving the project team the lab cost of \$12.50.

Total destructive testing cost could then be calculated per mile. This total of \$88.50 (\$76 per mile plus lab costs) was the number used in all the project team's models and graphs.

Nondestructive Testing Cost Formulation

To determine the test cost for destructive testing all aspects of the testing needed to be taken into consideration. The initial investment, field work costs, lab work costs, and destructive verification.

Initial investment costs consist purely of the cost of equipment needed to be purchased in order to first begin with nondestructive testing. Three major pieces of equipment that are necessary in order to perform nondestructive testing are; (1) custom vehicle, (2) falling weight deflectometer, and (3) ground penetrating radar. The custom vehicle and falling weight deflectometer are often considered to be one since the falling weight deflectometer is attached in the rear of the vehicle. These two pieces of equipment together according to industry standards cost approximately \$180,000. The ground penetrating radar is set at a price of \$30,000.

Field work for nondestructive testing was formulated by calculating the number of workers needed for nondestructive testing, their pay rates, and amount of time it would take a nondestructive testing crew to test 1 mile of asphalt. Unlike destructive testing, nondestructive testing only requires one person in the field to perform the tests. This person is a trained vehicle operator, and as industry standards of 2004 denote would have an average pay rate of \$25. It was calculated that the time it takes to perform a nondestructive test on a 1 mile stretch of asphalt would be three minutes. This time takes into consideration the vehicle with attached trailer traveling at a average speed of 30mph and stopping two time to perform a nondestructive test and obtain a

reading for 30 seconds. This gives the total time of 3 minutes per mile in turn relating the project team's field work expense for nondestructive testing of \$1.25 per mile.

$$.05 \text{ hours} * \$25 = \$1.25 \text{ per mile field work}$$

Equation 5: Nondestructive Testing Field Cost

In addition to the cost of field work lab tests are necessary to determine the elasticity and rigidity of the asphalt. For nondestructive testing one lab technician is necessary. This lab technician working at a normal pace would take approximately 15 minutes to perform one lab test on one sample. One lab test is all that is necessary on one sample. Factoring in the industry standard wage for a trained lab technician of \$25 and the time per test, it is calculated that one lab test for destructive testing costs \$6.25. Two nondestructive tests per mile are necessary when determining the elasticity and the rigidity of an asphalt system so in turn two lab tests would be necessary giving the project team the lab cost of \$12.50.

$$.5 \text{ hours} * \$25 = \$12.50 \text{ per mile lab fee}$$

Equation 6: Lab Costs (DT and NDT)

Total nondestructive testing costs could then be calculated per mile. This total of \$13.75(\$1.25 + lab costs) was the number used in all the project team's models and graphs.

It should be noted that a destructive verification is necessary when performing nondestructive testing. Destructive verification, which consists of one destructive test, is performed when abnormalities or changes are found in readings taken while nondestructively testing. This number was not taken into consideration for cost per mile but was taken into consideration in future analyzing of results found and graphs created.

A set up and warm up time is necessary for nondestructive testing. This time was determined to be on average twenty minutes. This cost was calculated to a cost of \$8.33(labor) start up cost. This number was also not taken into consideration for cost per mile but was taken into consideration in future analyzing of results found and graphs created.

$$.33 \text{ hours} * \$25 = \$8.33$$

Equation 7: Start Up Costs for NDT

Results

The project work process was defined and tactics used to generate the necessary information from the data gathered. In this section results will be taken and organized in a way that can be easily analyzed. The results that originated from the project teams data were the costs associated with each form of testing. These costs will be detailed in the pages to follow.

Initial Investment Costs

Destructive Testing

For each of the testing processes an initial investment cost was necessary in order to begin a certain form of testing. For destructive testing the initial investment cost is much lower than that of nondestructive testing.

There are three necessities when outfitting a highway department or contractor for destructive testing. These items are; (1) coring rig, (2) truck to mount the coring rig in and carry crew, (3) and lastly a truck to carry patching materials and crew. Coring rig according to industry standards set in 2004 is priced at 10,000. Truck expenses may fluctuate anywhere from \$25,000 each to much more for dump truck type heavy duty vehicles. However, for the project team's assumptions the trucks were estimated at a total cost of \$60,000 for both vehicles.

This therefore sets the initial investment cost of destructive testing at \$70,000. This rate was taken into consideration for all models and graphs created.

Nondestructive Testing

The initial investment cost of nondestructive testing was found to be much higher than that of destructive testing. Like destructive testing nondestructive testing also requires three major pieces of equipment. However, for nondestructive testing the custom vehicle and falling weight deflectometer can be considered one piece of equipment. There the cost of van including the falling weight deflectometer is estimated by 2004 industry standards at \$180,000. In

addition to the falling weight deflectometer and vehicle, ground penetrating radar is also necessary to perform nondestructive testing. This ground penetrating radar as set by 2004 industry standards was estimated as costing \$30,000.

This therefore sets the initial investment cost of nondestructive testing at \$210,000. This rate is much higher than that of destructive testing and this number generated was taken into consideration for all models and graphs created.

Cost Distributions	NDT	DT
Trucks for coring Rig and Patching Crew		\$60,000
Coring Rig		\$10,000
Custom Vehicle with Falling Weight Deflectometer	\$180,000	
Ground Penetrating Radar	\$30,000	
Total Costs:	\$210,000	\$70,000

Figure 14: Equipment Cost Comparison

Field Costs

Destructive Testing

The cost of destructive testing field work was determined through the process of determining the cost of destructive testing labor per mile. This was generated by including all the necessary labor wages for field workers and the time necessary to test one mile using the destructive testing process. Wages like all other wages were taken from the 2004 industry standard. Field work necessary for destructive testing consists of four laborers in the field. Two workers to obtain the coring sample and two others in the patching truck filling holes left from the coring sample. All workers are assumed to be paid at a rate of \$25 dollars per hour. It was calculated in the project team's work performed that

it would take 46 minute to destructively test a one mile stretch of asphalt.

Therefore the project team's cost per mile for field work for destructive testing was calculated at \$76 dollars per mile.

$$.76 \text{ hours} * \$100 = \$76 \text{ per mile field work}$$

Equation 4: Destructive Test Field Work Cost

Nondestructive Testing

Nondestructive field costs were calculated using the same method to that of destructive testing. The cost of nondestructive testing field work was determined through the process of determining the cost of nondestructive testing labor per mile. This was generated by including all the necessary labor wages for field workers and the time necessary to test one mile using the nondestructive testing process. Wages like all other wages were taken from the 2004 industry standard. In the process of nondestructive testing only one person is necessary in the field to perform the tests. This persons needs to be a trained vehicle operator. The constant rate of \$25 dollars per hour was assumed. Previously in the project team's work performed it was calculated that time necessary to perform a 1 mile nondestructive test on an asphalt system would be 3 minutes. Taking these numbers into consideration a nondestructive field cost of \$1.25 per mile was calculated.

$$.05 \text{ hours} * \$25 = \$1.25 \text{ per mile field work}$$

Equation 5: Nondestructive Testing Field Cost

Lab Costs (Destructive and Nondestructive)

Lab costs for both destructive and nondestructive testing are the same. The rate determined was calculated using pay wages taken from the 2004

industry standard for asphalt lab technicians.¹⁰ This rate of \$25 dollars per hour was then divided by the amount of time necessary to perform a certain lab test for each method of testing. This rate, since the time for each type of testing both destructive and nondestructive are similar, gives the project team a rate of \$6.25 per test.

Total Test Costs

Total test cost per mile was determined by calculating the field work costs plus lab costs for each type of testing per mile. For destructive testing cost per mile was determined as \$88.50, and for nondestructive testing the cost per mile was determined as \$13.75 per mile. These results enabled the project team to analyze the different costs of testing and make future recommendations.

	Destructive	Non Destructive
Cost Per Mile of Fieldwork	\$76.00	\$1.25
Cost Per Mile of Lab Work	\$12.50	\$12.50
Total Cost Per Mile	\$88.50	\$13.75

Figure 15: Comparison of Test Costs

Analysis

Results were analyzed by cost per mile and total cost in order to understand the cost benefits of both destructive and nondestructive testing. The team used the cost per mile to compare the cost of testing certain lengths of asphalt systems. To compare this data in terms of cost per mile of continuous testing set up time and warm up time would need to be taken into consideration for both systems of testing. A set up and warm up time is necessary for

¹⁰ Mallick, Rajib. Interviewed by authors. Worcester, MA, April 12, 2005.

nondestructive testing. This time was determined to be on average twenty minutes. This cost was calculated to a cost of \$8.33 start up cost. In addition to start up cost destructive verification was also taken into consideration when formulating the graph “Cost Per Mile”.

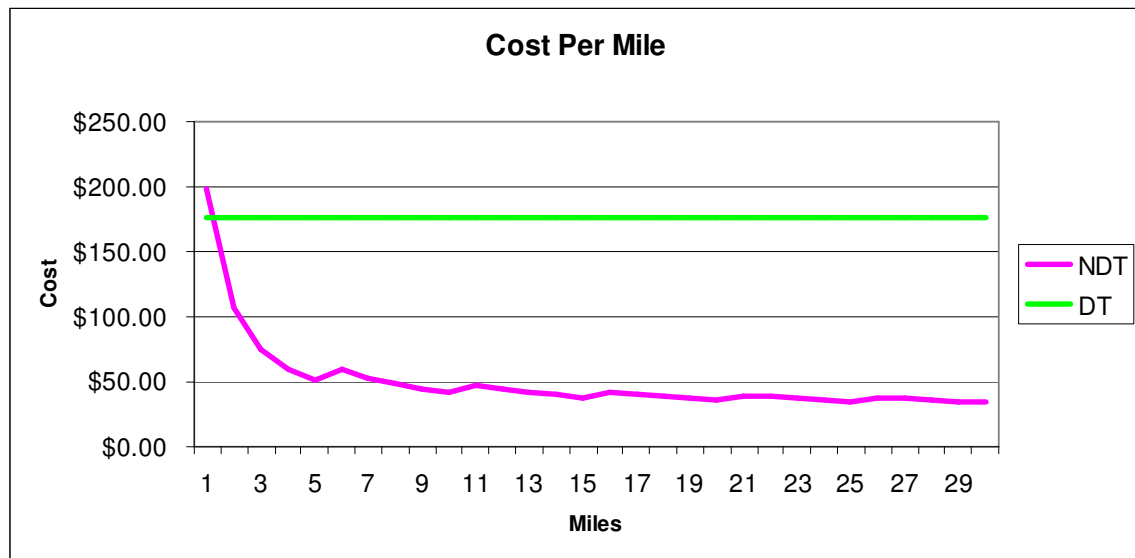


Figure 16: Cost Per Mile of Tests

As seen above the graph shows the cost per mile for both destructive and nondestructive testing. Destructive testing is a linear expense due to the fact that there is no start up cost or verification testing cost. Therefore the cost per mile holds steady at \$177 per mile.

However, nondestructive testing is not a linear cost. A start up cost is incurred at the beginning of each testing time and destructive verification test is incurred at certain points as well. Destructive verification is implemented two times one to five miles testing. After five total miles every five miles after that one more destructive verification is incurred to assume abnormalities or a change in rigidity or elasticity. As seen nondestructive testing quickly becomes less expensive than destructive testing even with additional costs incurred with

nondestructive testing. Even before one total mile of testing, nondestructive testing becomes more economical than destructive testing.

Next, the total cost of the test was analyzed. This graph shows total costs for depicted miles of asphalt tested. Numerous conclusions can be drawn from this graph. As seen in graph “Total Cost” nondestructive testing is far more cost effective over long term use than destructive testing.

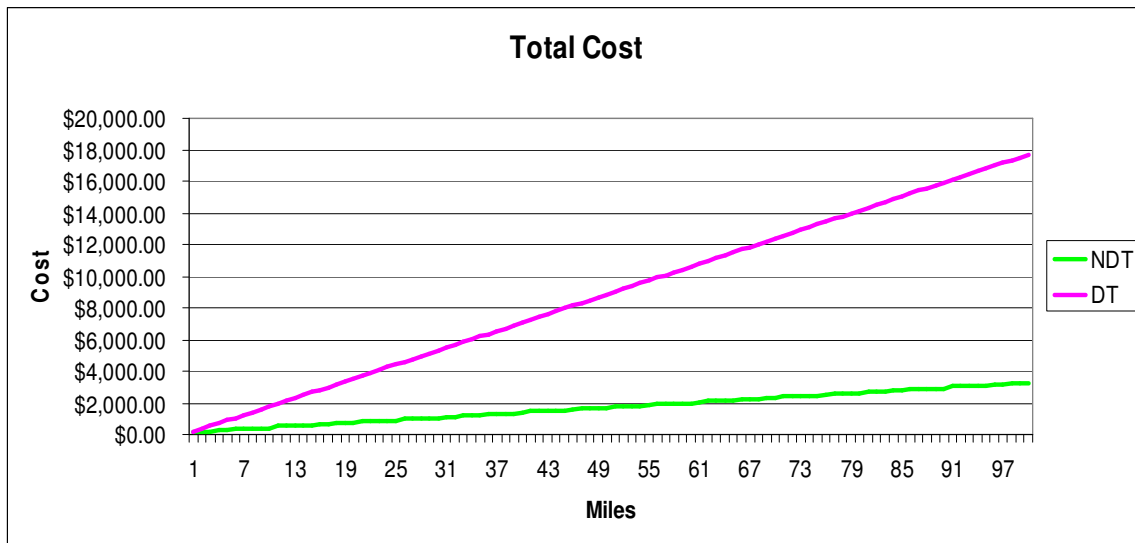


Figure 17: Total Cost to 100 Miles

More specifically if Total cost graph is evaluated at a higher intervals and overall higher number of miles tested, number of miles necessary to be tested to pay for initial investment can be calculated.

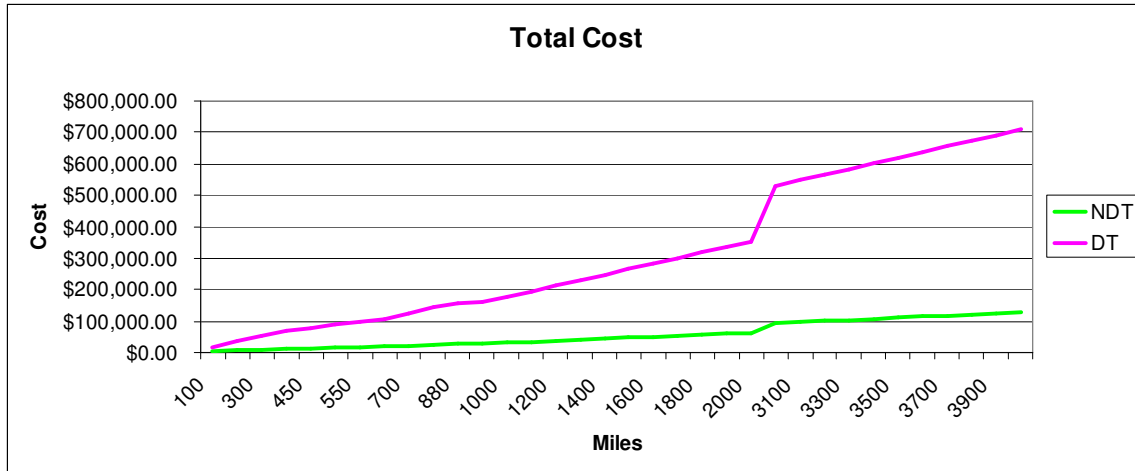


Figure 18: Total Cost to 4000 Miles

At approximately 880 total miles tested the initial investment spent on nondestructive testing equipment along with cost per test surpasses the initial investment of destructive testing along with cost of testing. At this point of 880 miles, nondestructive testing costs less in total than destructive testing.

Conclusions and Recommendations

The work performed by the project team represents an assessment of the costs associated with both destructive and nondestructive testing. The cost per mile of nondestructive testing is far less than the cost of destructive testing. There are also fewer laborers involved in the nondestructive testing method analyzed. The decrease in labor also leads to less chance for an accident on the road which means increased safety. Moreover, since the one laborer needed in nondestructive testing does not need to leave the vehicle, the safety level of this test is further increased.

	Cost	Human Resources	Safety	Time
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Nondestructive Testing	\$13.75	1 Laborer	Higher	.05 mph
Destructive Testing	\$88.50	4 Laborers	Lower	.76 mph

Figure 19: Completed Comparison Matrix

In all the categories of the comparison matrix, nondestructive testing scores better than destructive testing.

The project team therefore recommends that nondestructive testing be used by municipalities and engineering firms that have the option between nondestructive testing.

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Appendix A – Interview Questionnaires

This appendix includes the interview questionnaire when doing research on destructive and nondestructive testing.

Destructive Testing Questionnaire

Questions are cost, equipment, and result viability related:

(1) What equipment is necessary for getting samples, and how much does this equipment cost?

(2) How many people must be in the field at one time to obtain a sample? How many hours does it take? How much do they usually get paid, (are they engineers or laborer type workers), what is their rate per hour?

(3) How many total tests are necessary to gain an accurate estimate of a certain length of roadway? (Maybe a specific number per mile)

(4) How much time does each individual test take?

(5) Are there any safety risks?

(6) Is there a set standard of accuracy for these tests and what is the accuracy (%)?

Nondestructive Testing Questionnaire

Questions are cost, equipment, and result viability related:

(1) What equipment is necessary for getting samples, and how much does this equipment cost?

(2) How many people must be in the field at one time to obtain a sample? How many hours does it take? How much do they usually get paid, (are they engineers or laborer type workers), what is their rate per hour?

(3) How many total tests are necessary to gain an accurate estimate of a certain length of roadway? (Maybe a specific number per mile)

(4) How much time does each individual test take?

(5) Are there any safety risks?

(6) Is there a set standard of accuracy for these tests and what is the accuracy (%)?